A PIEZOELECTRIC CANTILEVER WITH HELMHOLTZ RESONATOR FOR
A SOUND-TRIGGERED WAKE-UP SWITCH

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Abstract: This paper reports on a piezoelectric (PZT) cantilever with Helmholtz resonator (HR) for a sound-
triggered wake-up switch which detects a specific frequency tone with low standby power consumption. The size
of the cantilever was 1500 µm × 1000 µm × 2 µm. Both resonant frequencies of the cantilever and the HR were
designed to be the same in order to improve the output voltage. The sensitivity of the fabricated cantilever with
HR was 41 mV/Pa at 2.1 kHz.

Keywords: Wake-up switch, Piezoelectric cantilever, Helmholtz resonator.

INTRODUCTION

An acoustic diagnosis is used for monitoring of abnormalities in industrial facilities, because
abnormality of facilities emits a sound at specific frequency [1]. For example, gas leakage from pipeline
generates a sound at frequency below 10 kHz [2]. Wireless sensor network (WSN) system facilitates the
installation of the acoustic diagnosis system. However, always-on sensor nodes are not suitable for WSN due
to its power consumption. A switch is required to wake-up the sensor nodes with low power consumption when the environment surrounding the sensor node changes. The wake-up switch is attained with a combination of a flow sensor and a MOS FET.

For the acoustic diagnosis, a wake-up switch which is triggered by the abnormal sound at specific frequency
is thought to be effective. Conventional sound pressure sensors containing a diaphragm with piezo resistor or capacitor as a sensing element have high sensitivity [3]. However, it is not suitable for a wake-
up switch due to its high power consumption. Piezoelectric diaphragm type sensors which fulfill low
power consumption have been also developed, but the sensitivity is too low for our proposed wake-up switch
[3].

We propose a sound sensor using an ultra-thin piezoelectric cantilever with HR for a wake-up switch which is triggered by a specific frequency tone for monitoring of facilities (Figure 1). Both resonant frequencies of the cantilever and the HR are designed to be the same in order to improve the sensitivity [4]. Thus, the sensor can detect a specific frequency tone with low power consumption because of its high sensitivity and high Q factor.

In this paper, we designed and fabricated a PZT cantilever. The fabricated PZT cantilever with HR was
evaluated.

PRINCIPLE

PZT cantilever with HR

Figure 2 (a) shows the concept of the switch using a PZT cantilever with HR. The cantilever generates
piezoelectric voltage when it is deformed by sound pressure. Deformation of the cantilever at its resonant
frequency is enhanced when the cantilever is attached to the neck of the HR whose resonant frequency is the
same as that of the cantilever [4].

PZT cantilever

Figure 2(b) shows the concept of a PZT cantilever. The PZT layer is formed on the surface of the
cantilever structure. When there is a pressure difference between the top and bottom surfaces of the
cantilever, force is applied to the cantilever and the cantilever is deformed. The piezoelectric voltage is


Figure 1 Concept of a sound switch using a PZT cantilever with Helmholtz resonator.
where $E$ and $\rho$ are the young’s modulus and density, respectively, as show in Figure 2(b) [6].

**Helmholtz resonator**

Helmholtz resonance occurs in a resonator with a neck and a chamber as shown in Figure 2(c). It can be modeled approximately by a one degree-of-freedom oscillatory system. The air in the neck and that in the chamber are represented by a mass and a spring, respectively. The resonance frequency of an HR is expressed in equation (2)

$$f_H = \frac{c}{2\pi} \sqrt{\frac{S}{(N+\Delta N)V}}$$

where $c$ is the acoustic velocity as show in Figure 2(c) [7].

**DESIGN AND FABRICATION**

**Sensor design**

Figure 3 shows the design of the sensor using the PZT cantilever with HR. The size of the cantilever and the total size of the device were $1000 \ \mu\text{m} \times 500 \ \mu\text{m} \times 2 \ \mu\text{m}$ and $20 \ \text{mm} \times 20 \ \text{mm} \times 9 \ \text{mm}$, respectively. The size of the neck and chamber were $\varphi 2.0 \ \text{mm} \times 2 \ \text{mm}$ and $\varphi 10 \ \text{mm} \times 7 \ \text{mm}$, respectively. Both resonant frequencies of the cantilever and HR were designed to be 2.0 kHz.

**Fabrication process**

The fabrication process for the piezoelectric cantilever is shown in Figure 4. We have fabricated the piezoelectric cantilevers from multilayers of Pt/Ti/PZT/Pt/Ti/SiO$_2$, deposited on a Silicon on Insulator (SOI) wafer (1.3/1/400 \text{\mu m}) as shown in Figure 4(a) [8]. Firstly, the Pt/Ti top electrode was etched as shown in Figure 4(b). Secondly, The PZT film was etched. The Pt/Ti bottom electrode and the SiO$_2$ were etched. Au was deposited and patterned for bonding pads. Thirdly, device Si layers and buried oxide were etched as shown in Figure 4(c). Finally, handle Si/SiO$_2$ layers were etched from the backside to release the piezoelectric cantilever as shown in Figure 4(d). Photograph of the fabricated cantilever chip and an SEM image of the cross-sectional view of the cantilever are shown in Figure 5(b)(c), respectively. The capacitance of the fabricated cantilever was 1.7 nF.

**Fabricated sensor**

The HR neck and chamber were fabricated from a wiring substrate and a UV cured acrylic, respectively. Figure 5(a) shows a photograph of the fabricated...
Figure 5 (a) Photograph of the fabricated device. The sensor chip is fixed on a substrate. The substrate is attached to an HR volume. (b) Photograph of the fabricated cantilever chip. (c) SEM image of the cross-sectional view of the cantilever.

Figure 6 (a) and (b) Photograph and schematic of the experimental setup for measuring the sensor response to sound pressure.

sensor chip on HR.

EXPERIMENT AND RESULTS

Experimental setup

Photograph and concept of the experimental setup to measure the sensor response to sound pressure are shown in Figure 6(a), (b), respectively. Sound wave was applied from a speaker (FOSTEX FT17H) and calibrated by a microphone (Bruel&Kjar 2690-A-0S1). The device was oriented to face the speaker. We applied sound waves with frequencies ranging from 1 kHz to 4 kHz. The output voltage was measured using a network analyzer (Agilent 4395A) through a charge amplifier. Band pass filter from 10 Hz to 100 kHz was used in the measurement.

Experimental Results

Relationship between the frequency of the sound wave and the output voltage per unit sound pressure is shown in Figure 7(a). In this figure, the voltage per unit sound pressure is calculated by dividing the output voltage by the sound pressure amplitude measured by the commercial microphone. The response of the sensor without HR was also measured in order to evaluate the effect of the HR. Both output of the sensor with/without HR had maximum value at 2.1 kHz. Thus, the resonant frequency was thought to be 2.1 kHz, which was the same as the designed value.
The sensitivity and Q factor of the device with HR were 44.7 mV/Pa and 26, respectively. On the other hand, the sensitivity and Q factor of the device without HR were 9.4 mV/Pa and 10, respectively. Compared with the PZT cantilever without HR, the output voltage of the PZT cantilever with HR was approximately 5 times larger. The Q factor of the PZT cantilever with HR was also approximately 3 times larger than that of the cantilever without HR. These results indicated that HR improved the signal of the cantilever only around the resonant frequency.

Additionally, the relationship between the output voltage of the sensor and the applied sound pressure at the resonant frequency was measured. By changing the applied voltage level to the speaker, the sound pressure was controlled. We applied sound pressure from 0.1 Pa to 1.6 Pa at 2.1 kHz. As the result, a linear correlation between the output voltage and the pressure level can be observed as shown in Figure 7(b). The fitted line was $V_{(mV)} = 41 P_{(Pa)}$.

These results indicate the potential to apply the sensor to the wake-up switch when a sound wave of sub-pascal at 2.1 kHz is applied.

CONCLUSION

The PZT cantilever with HR was designed and fabricated for a sound triggered switch. The size of the PZT cantilever was 1500 µm × 1000 µm × 2 µm, whose resonant frequency was 2.1 kHz. The sensitivity and Q factor of the fabricated sensor were 44.7 mV/Pa and 26, respectively at 1.6 Pa. These values were approximately 5 times and 3 times larger than those without HR. The sensitivity was proportional to the applied sound pressure. Our proposed sensor can be used as a wake-up switch when a sound wave of sub-pascal at certain frequency is applied.

ACKNOWLEDGMENTS

A part of this work was supported by New Energy and Industrial Technology Development Organization (NEDO). The photolithography masks were fabricated using the EB lithography apparatus of the VLSI Design and Education Center (VDEC) of the University of Tokyo.

REFERENCES


